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Fifth Semi-Annual Progress Report
for the
Scripps Institution of Oceanography's
University Research Initiative (URI)
entitled
"OCEAN REMOTE SENSING AND MODELING"

ONR Contract No. N00014-86-K-0752

Co-Principal Investigators:

James J. Simpson
Geoffrey K. Vallis
Warren B. White

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INTRODUCTION

This is the Fifth Semi-Annual Report of the Scripps Institution of Oceanography's University Research Initiative (URI) entitled *Ocean Remote Sensing and Modeling* [ONR Contract number N00014-86-K-0752]. The report covers the performance period 15 September 1988 - 15 March 1989 and contains a set of unedited technical statements prepared by individual scientists working on the URI. For your convenience, these statements are arranged in alphabetical order and separated by index tabs.

Should any questions arise concerning this report, please call them to the attention of:

Dr. J. J. Simpson
A-030
Scripps Institution of Oceanography
La Jolla, CA 92093-0230

Office telephone: (619)534-2789
Laboratory telephone: (619) 534-5426

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URI EXECUTIVE COMMITTEE:

Dr. James J. Simpson
A-030
Scripps Institution of Oceanography
La Jolla, CA 92093

Dr. Geoffrey K. Vallis
A-021
Scripps Institution of Oceanography
La Jolla, CA 92093

Dr. Warren B. White
A-030
Scripps Institution of Oceanography
La Jolla, CA 92093

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Dr. Moustafa Chahine
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, CA 91109

Dr. Edward A. Frieman, Director
Scripps Institution of Oceanography
A-010
La Jolla, CA 92093

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Naval Ocean Research and
Development Activity
NSTL, MS 39529-5004

Professor William A. Nierenberg
A-021
Scripps Institution of Oceanography
La Jolla, CA 92093

Professor James J. O'Brien
Meteorology Annex
Florida State University
Tallahassee, FL 32306-3041

Dr. Steven Payne
Naval Environmental Prediction
and Research Facility
Monterey, CA 93943-5006

Mr. Frank J. Wentz
Remote Sensing Systems
Suite 220, 1101 College Avenue
Santa Rosa, CA 95404

Dr. Alberto Zirino
Chemistry and Environmental
Sciences Division
Code 5132
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SCRIPPS INSTITUTION OF OCEANOGRAPHY:

Office of Contract and Grant Administration
A-010
Scripps Institution of Oceanography
La Jolla, CA 92093

IN SITU – OCEAN REMOTE SENSING

Mid-Term URI Progress Report
15 September 1988 – 15 March 1989

James J. Simpson

I. SCIENTIFIC ACTIVITY

A. Completed Analyses:

Five manuscripts have been completed and submitted to journals for publication. Listed below are the titles, abstracts, and journal for each of these manuscripts.

1. Simpson, James J.: The Pacific North American Teleconnection Between Equatorial ENSO and Mid-Latitude North Pacific Coastal Warming Events. *Deep-Sea Research*.

Abstract. The large-scale structure of the California Current during the 1982-83 mid-latitude North Pacific coastal warming event showed several persistent (>16 months), anomalous conditions: positive sea surface temperature anomalies (1-2.5°C), depression of the inshore thermocline (~50 m), anomalous high inshore steric heights (~1.05 dyn. m), anomalous high sea levels (~25 cm), positive subsurface temperature anomalies (3-4°C), negative salinity anomalies (0.1-0.3‰), and positive dissolved oxygen anomalies (0.5-1.5 ml/l). The magnitudes of the subsurface anomalies generally are much larger than those of the surface anomalies. The cross-shelf length scales of the subsurface anomalies vary between 300 and 500 km. During this same period, pronounced negative sea surface temperature anomalies (2-3°C) developed simultaneously in the central mid-latitude North Pacific. The anomalies, characteristic diagrams, and sign reversals in the salinity and oxygen anomalies are consistent with enhanced onshore transport of Pacific Subarctic water from the offshore California Current. The source of this water is primarily from the west-northwest (i.e., an intensified West Wind Drift). The subsurface anomalies were produced dynamically by a depression of the inshore thermocline which results from convergence of mass at the coastal boundary. The surface anomalies, however, were produced by a combination of dynamical and local thermodynamical processes. Observed anomalous atmospheric forcing, as reflected in the 700 mb height anomaly and in negative upwelling indices, is consistent with enhanced onshore transport from offshore California Current. All the data support the conclusion that the expansion and intensification of the Aleutian low and decrease in strength of the North Pacific High produced an anomalous basin-wide atmospheric circulation, which coupled directly to the large-scale wind-driven oceanic circulation, to produce a major component of the North Pacific coastal warming response observed during 1982-83. Nearly identical mid-latitude atmospheric forcing and oceanic responses were observed during the 1940-41 analog event. A simple model of resonant (El Niño) and anti-resonant (anti-El Niño) wind-induced forcing of the California Current, achieved through enhanced (warm events) or diminished (cold events) onshore transport of waters from the West Wind Drift primarily within the latitude band 45-55°N, explains most of the observed warm and cold episodes in the California Current. The expansion of the Aleutian Low during most of these periods, however, is likely associated with the contemporaneous equatorial ENSO events.

2. Simpson, James J., and Christopher Humphrey: A New Cloud Screening Algorithm for AVHRR Imagery. *Journal of Geophysical Research*.

Valid estimates of sea surface temperature (SST) from AVHRR are critically dependent upon the identification and removal of clouds from parent images. Previous cloud-screening algorithms have demonstrated varying degrees of success, the effectiveness of the particular method used being critically dependent upon cloud type. Contamination from cirrus clouds, for example, has been a major deficiency in previous methods. A robust, new algorithm for cloud masking has now been developed which is very effective at removing cloud contamination from images regardless of cloud type. The method, which evaluates every pixel in the image, is statistically reproducible, efficient, and minimizes subjective evaluation. The results also show that the algorithm is not regionally specific. The basis for this new method is presented and applications to AVHRR data, including comparisons with previously used methods, are shown.

3. Lynn, Ronald J., and James J. Simpson: The Influence of Bathymetry Upon the Flow of the Undercurrent off Southern California. *Journal of Geophysical Research*.

Complex bathymetric features offshore of southern California have a pronounced effect upon the flow of the California Undercurrent. Geostrophic dynamics and water mass characteristics are used to reveal the various paths of flow and spread of Undercurrent waters for a July 1985 survey. Undercurrent waters are identified by relatively high spiciness and low dissolved oxygen at densities between $\sigma_t = 26.4$ and 26.9 (~200 to 400 m). A jet-like core of flow follows the continental slope within the California Bight and exits the Bight through a gap in the Santa Rosa-Cortes Ridge. Mixtures that include Undercurrent waters exit the Bight through other gaps in the bathymetric ridge and about the southern end of the ridge. Dynamic instabilities develop about the ridge which result in the diversion of Undercurrent waters offshore beneath the California Current and into the offshore mesoscale eddy field. The offshore subsurface diversion of undercurrent waters and their inclusion in the offshore mesoscale eddy field are also found in the long term mean distributions for July.

4. Simpson, James J., and Ronald J. Lynn: A Mesoscale Eddy Dipole in the Offshore California Current. *Journal of Geophysical Research*.

There is a transition zone in the California Current system between inshore coastal and offshore oceanic flow. This transition zone is associated with the main core of the California Current and is populated with offshore mesoscale eddies. Both the layer and modal structure of isolated eddies and dipole eddy pairs found within the transition zone are examined using water mass analysis (spiciness and dissolved oxygen) and normal mode decomposition. The analyses show that these offshore mesoscale eddies are modally rich structures whose cores contain California Undercurrent water. The results also support the conclusion that a bathymetrically-induced instability of the California Undercurrent is a likely generation mechanism for the offshore eddies. The similarity between long-term mean conditions (Cal-COFI) and conditions observed during January, 1981 and July, 1985, coupled with the bathymetric effects, provide a plausible explanation for the recurrence of offshore mesoscale eddies at preferred locations within the transition zone.

5. Wahl, Darrin D., and James J. Simpson: Physical Processes Affecting the Objective Determination of Near-Surface Velocity from Satellite Data. *Journal of Geophysical Research*.

A more robust implementation of an objective method for estimating sea surface velocities from remotely sensed sea surface temperature (SST) patterns is given. The method assumes, like previous methods, that the motion of thermal features results from advection. Other near-surface processes (i.e., diffusion and air-sea heat exchange), however, can also affect the near-surface thermal structure. It therefore becomes necessary to determine how

these physical processes affect the perceived velocity determined from thermal gradient structure. Models were developed to quantitatively analyze the method's relative sensitivity to the degradation of thermal features due to near-surface physical processes. The results are used to quantify the attainable accuracy of the method for estimating near-surface velocity.

B. Continuing Analyses:

Currently, we are analyzing about 90 days of process-oriented experiments taken as part of the URI. We anticipate that this work will be completed within the next 18 months.

II. EDUCATION

A. Graduate Student:

Mr. Darrin Wahl, my URI-sponsored graduate student, has done well on his thesis topic: "Velocity Estimates from Space: Sensitivity to Computational Methods and Near-Surface Physical Processes." Mr. Wahl should complete his studies within the next 6 months.

B. Post-Doctoral Fellow:

Dr. Barbara Eckstein, my URI-sponsored post-doctoral fellow, should complete her work in the next 3-4 months. One paper, "Anatomy of CZCS Processing: An Integrated Method for the Determination of Pigment Concentration," by Eckstein and Simpson, will be submitted shortly for publication.

III. ADMINISTRATIVE

During the past year I have served as Secretary of the Executive Committee. As such, I have been the principal liaison between the Executive Committee and UCSD Contracts and Grants, CalSpace Contracts administrative personnel, the ONR Resident Representative Mr. R. Bachman, and ONR Washington. Preparation of reports, budget reviews, individual investigator requests for budgetary reprogramming authority, and the like constituted the major part of this administrative function.

Summary of modelling and theoretical efforts.

G. K. Vallis

The preliminary stages of development of a quasi-geostrophic model of the California Current region with realistic geometry and bathymetry have been completed, in collaboration with W. Holland of NCAR. This model is eddy resolving ($1/6$ degree horizontal resolution) within the California Current region. It is nested with a non eddy resolving model of the entire North Pacific basin. The nesting procedure provides boundary conditions for the limited area model by allowing a fully two way interaction between the two regions. A variety of numerical integrations have been performed with the model. One notable result is the production of a California undercurrent, in roughly its observed location. Analysis indicates it is a consequence of eddy-topographic interactions. Note that gravity wave activity is absent from the model and plays no role. Manuscripts are in preparation. Extension of the domain of high resolution to other areas is being considered.

A study of the seasonal and interannual variability of the California Current season with a reduced gravity model was completed (Pares-Sierra and O'Brien, 1989). An adiabatic primitive equation model of the same region was also developed by Vallis and Pares-Sierra. The model is a multi-layer primitive equation model in isopycnal co-ordinates (sometimes called a stacked shallow water model). A number of preliminary experiments were performed although the lack of computer time in the last half of the year has prevented extensive experimentation.

A new numerical technique was developed for the fast solution of non-separable elliptic equations in irregular domains. Such equations are ubiquitous in many branches of physics aside from oceanography (e.g. reactor physics, in plasma problems). The new technique relies on the combined use of a fast iteration and the capacitance matrix method. For many problems the new method proves to be 3 – 5 times faster than traditional techniques (Pares-Sierra and Vallis, 1989).

In part because of the unavailability of computer resources, a greater emphasis has been placed on theoretical work than might otherwise. In particular, a new method was developed for the construction of stable solutions to the equations of motion. The method involves certain modifications of the equations of motion such that the potential vorticity is

conserved on parcels, yet energy monotonically grows or decays. The final state will be a stable configuration with (except for certain caveats discussed in Vallis et al, 1989) the same vortex topology as the initial state. The method is applicable for many forms of the equations of motion (two-dimensional, three dimensional, quasi-geostrophic. shallow water etc.). A variety of experiments were performed (Carnevale and Vallis, 1989).

Finally, a possible parameterization for the action of gravity waves was proposed. In regions of the fluid where vortex activity is high, the parameterization acts to reduce energy while conserving potential vorticity. This is very similar to the process of gravity wave adjustment to a geostrophic flow, suggesting its use as a possible parameterization in low resolution models.

Papers acknowledging ONR support

Pares-Sierra A. and O'Brien, J. 1989: The seasonal and interannual variability of the California Current System. A numerical model. *J. Geophys. Res.*, 94, 3159-3180.

Pares-Sierra, A. 1989: On the equatorial origin of some of the Rossby wave activity in the midlatitude Pacific Ocean. Submitted to *J. Geophys. Res.*

Pares-Sierra A. and Vallis, G.K. 1989: A fast semi-direct method for the numerical solution of non-seperable elliptic equations in irregular domains. *J. Comp. Phys.*, (in press).

Vallis, G.K., Carnevale, G.F. and Young, W. 1989: Extremal energy properties and construction of stable solutions of the Euler equations *J. Fluid. Mech.* (in press).

Carnevale, G.F. and Vallis, G.K. 1989: Pseudo-advective relaxation to two-dimensional stable states. Submitted to *J. Fluid. Mech.*

Vallis, G.K. and Holland, W. Nested models of the ocean circulation: Techniques and examples (in preparation)

Holland, W. and Vallis, G.K. An eddy resolving model of the California Current system (in preparation)

**University Research Initiative
Semi-Annual Progress Report
June, 1989**

**Warren B. White
Scripps Institution of Oceanography
A030, UCSD, La Jolla, CA 92093**

1. Present Research

Over the past six months, real GEOSAT altimetric sea level differences collected over the first one year period of the Exact Repeat Mission (ERM), from November, 1986-October 1987, have been assimilated into a wind driven realistic quasi-geostrophic numerical model of the California Current, following from the necessity of gridding these data onto a regular grid from an irregular grid (i.e., the ascending and descending tracks of the GEOSAT altimeter) in such a way that the interpolated sea level information is dynamically consistent. This so-called dynamical interpolation has numerous advantages over statistical interpolation now employed (e.g., White *et al.*, 1989b) : i.e., it allows the wavenumber/frequency content of the mesoscale eddy activity to be more faithfully represented; it allows more observational information (e.g., wind stress curl) than just altimetric sea level differences to be brought to bear upon the interpolation process; it allows both the barotropic and the internal baroclinic modal structure to be detected; and it allows the resulting interpolated fields to be analyzed for their dynamical content (i.e., computing the vorticity and kinetic energy budgets). In the present effort, continuous model/data assimilation was conducted in a nowcast mode, where only data from the past were used to determine the present state; as such, it represented a test of the methods to be used in future nowcast operations using real-time altimetric sea level data.

Details of the result of this effort is as follows. Prior to assimilation, observed GEOSAT ERM altimetric sea level differences

for the initial one year period November 1986-October 1987 were referenced using both the mean sea level and the long wave along-track information from the model, thereafter continuously assimilated into the subsequent integration of the model for the same time period. The ocean model used in this study was a realistic wind driven, non-eddy resolving, quasi-geostrophic numerical ocean model of the California Current. The decision to conduct continuous assimilation of the GEOSAT ERM altimetric sea level into a model of this type was based upon the results of the analysis of GEOSAT ERM altimetric sea level differences (White and Tai, 1989). In the latter study, altimetric sea level differences had been interpolated statistically (i.e., using optimum interpolation) onto a regular 1° latitude/longitude grid for the same one year period used in the present study. In that earlier work, approximately 76% of the total variance associated with the mesoscale eddy activity observed in the California Current region was found dominated by the annual and semi-annual cycles of variability. Another 15% of the variance was associated with period time scales of 3-5 months. Despite these relatively long period time scales, the spatial scales were dominated by wavelengths of 500-1000 km; these scales of relatively short wavelength and long period were partially due to the high pass filtering of the GEOSAT ERM altimetric sea level along the repeat altimetric tracks required to remove the residual orbit error along each of the tracks. Anyway, these dominant time and space scales arguably suggested that the dominant variability in the GEOSAT ERM altimetric sea level data set was related to wind stress/bouyancy forcing rather than intrinsic instability processes or to remote/local Kelvin wave activity. Moreover, it had been demonstrated earlier by White *et al.* (1989a) that the GEOSAT ERM was capable of observing mesoscale eddy activity only on wavelength scales greater than approximately 280 km, which was the Nyquist wavelength of the track separation distance of the GEOSAT ERM. This wavelength scale was larger than the Nyquist wavelength (i.e., 200 km) resolved by the non-eddy resolving numerical model and much larger than that resolved by an eddy resolving model (i.e., approximately 40 km). Therefore, it was deemed reasonable to proceed with the

assimilation of the GEOSAT ERM altimetric sea level data into the wind driven, non-eddy resolving, quasi-geostrophic numerical model of the California Current.

Prior to assimilation, it was necessary to demonstrate that the integration of the numerical ocean model under realistic conditions yielded space/time statistics that were similar to those observed; otherwise, it would hardly be appropriate to attempt an assimilation of the observed GEOSAT ERM altimetric sea level differences into the model. This was demonstrated by showing that the space/time statistics of the along-track altimetric sea level differences (along representative tracks) were similar to those space/time statistics determined from the model. Once this was established, and model/data assimilation was found sensible to carry forward, then the GEOSAT ERM altimetric sea level differences were referenced. In referencing the altimetric sea level differences, the model was again utilized, providing the annual mean, and long-wave (along-track) information, both to reference the GEOSAT ERM altimetric sea level differences and restore the long wave signal removed in the suppression of the residual orbit error. This procedure of referencing the altimetric sea level differences with the annual mean and the long-wave information determined from the model upgraded the importance of the model in this assimilation effort; i.e., not only was the model used directly in the assimilation process (i.e., to make the interpolation process be dynamically consistent), but it was also used in the definition of the reference for the altimetric sea level differences. As such, it became necessary to demonstrate that the model could simulate both the mean sea level and the large scale along-track variability, at least as well as any other method (e.g., from the observed relative dynamic height). This was done by comparing the model results with historical CalCOFI data.

2. Future Research

The present research is in support of the development of an experimental prediction capability (called ESOP, for Experimental Synoptic Ocean Prediction) for the synoptic mesoscale circulation of the upper ocean on a regional basis in the California Current.

proposed to the Navy for the three year period following the termination of the University Research Initiative.

The reason the California Current was chosen for this, is that the statistical and phenomenological nature of the synoptic ocean circulation in the California Current region is better known than in most other regions of the global ocean. This has been made possible by the intensive oceanographic research that has been conducted there over the past 40 years by SIO and other institutions on the west coast. Considerable progress has been made in describing and understanding the mesoscale eddy activity in the California Current through the simultaneous examination of both *in situ* and remotely-sensed data. This has lead, recently, to the development of a realistic, wind driven, eddy resolving prognostic model of the California Current, to be used in this study ,developed by Pares and Vallis (1989) at SIO under the University Research Initiative.

This realistic model of the California Curret is an extension of the 1-1/2 layer wind driven FSU model developed for the California Current region by Pares and O'Brien (1989). The present version of this model has been extended to 10 km resolution, with additional layers that allow baroclinic instability to exist in the model; moreover, it was possible to include the effects of bottom bathymetry on the synoptic circulation of the California Current. This model is driven by the synoptic wind stress computed from the synoptic wind analysis of FNOC. This wind-driven model reproduces much of the mean and statistical aspects of the synoptic mesoscale circulation in the California Current. An assimilation package, called "UPDATE" will be used with this model in the assimilation of GEOSAT ERM altimetric sea level into the model, thereby defining the phase of the mesoscale eddy activity in the model synoptic California Current.

Altimetric sea level data from the GEOSAT Exact Repeat Mission (ERM) must have extensive pre-processing applied to it before it can be assimilated into the prognostic model. A part of this pre-processing requires both the mean and the long wave portion of the data (along track) to be removed, yielding residual, high-passed, estimates of the altimetric sea level. Yet, before assimilation into

the model, these residuals must be referenced to a new mean and the long wave portion of the observations restored. This referencing is accomplished by using the mean and long wave information along track from the model itself. These referenced sea level residuals, as they become available in real time, are then combined with the model sea level after each time step in the model integration, with the latter seen to be updated by the former. This updating procedure occurs following the formalism of optimal interpolation used in meteorology (Lorenc, 1981).

The specific experimental products to be computed in real time (i.e., within a week of the present day) are tentatively given as follows, subject to change depending upon the needs of the users:

1. Horizontal distribution of surface dynamic topography;
2. Horizontal distribution of subsurface dynamic topography at standard levels in the upper 500 m ;
3. Offshore vertical sections (extending to 500 m) of along-shore currents at standard CalCOFI lines;
4. Offshore vertical sections (extending to 500 m) of the anomalous baroclinic structure at standard CalCOFI lines.

These weekly experimental products will be disseminated on a monthly basis to those interested scientists and institutions. Verification of the experimental products will be conducted in a hindcast mode initially, establishing that the model/data assimilation compares with *in situ* observation to within a specified error; this will be established before the first experimental products are put "on line". It is expected that critical review by the users of these experimental products will be important in their improvement.

3. References

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an eddy resolving numerical ocean model (Part I): Sea level differences. *J. Geophys. Res.*, (in review).

White, W.B., C.-K. Tai, and W.R. Holland, 1989b. Continuous assimilation of simulated GEOSAT altimetric sea level into an eddy resolving numerical ocean model. (Part II): referenced sea level differences. *J. Geophys. Res.*, (in review).

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